SPR – 0010(120)
RP 143, FC# 99-156

Evaluation of Potential Earthwork Savings in Road Design Using ROADZ

Prepared for

The Idaho Transportation Department
State Planning and Research Program

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September 30, 1999

Acknowledgement

The Technical Oversight Committee under the leadership of Mr. Steven C. Hutchinson, P.E., provided valuable guidance to this project and Mr. Greg Laragan, P.E., coordinated the various activities of this project. Their support is gratefully acknowledged.

Disclaimer

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EXECUTIVE SUMMARY

Designers hope to accomplish earthwork optimization, which includes cut and fill volumes and mass haul, in their road design. Commonly used road design software packages, however, cannot explicitly account for earthwork optimization. This is true of INROADS, the software used by the Idaho Transportation Department (ITD) for road design.

Small changes in elevations of vertical points of intersections (VPI) can result in significant earthwork savings when designing roads. ROADZ is a road design software that can optimize earthwork. ITD wanted to investigate potential earthwork savings from the use of this software. An agreement between ITD and Boise Statement University (BSU) was signed on 4 March 1999 that tasked BSU to conduct this investigation and present its results to ITD by 30 September 1999. This is the draft final report prepared under this contract.

According to the contract ITD provided data from three recent road design projects to BSU. One project is a 5 mile section on US 95 near Parma. The other two are on State Highway 3 in Nez Perce County from Arrow to Turkey Farm and from Turkey Farm to Little Potlatch Creek; both sections are about 2 miles long.

Data from the three test projects comprising the design profile grade and the original ground profile was entered into the ROADZ program. The earthwork optimizing program OPTEW, which is a component of ROADZ, was used to process the data and recommend a new roadway profile corresponding to an optimized mass diagram.

Savings between 50 to 60% in mass haul and 8 to 9% in cut and fill were realized on US 95 and the section of SH 3 between Turkey Farm to Little Potlatch Creek. The Arrow to Turkey Farm segment was not amenable to earthwork optimization using ROADZ because of significant full bench and retaining wall requirements.

Means of integrating OPTEW with ITD's road design process was investigated. Alternatives examined were the following: provide OPTEW with the ability to access intermediate binary files generated by INROADS, the road design software used by ITD, so that a seamless interface between road design and earthwork optimization is achieved, or use ROADZ and INROADS as stand-alone programs with the designer acting as the interface between the two programs.

With the likely adoption of the Engineering and Survey Exchange (EAS-E) data format by AASHTO in the near future, the technical oversight committee (TOC) responsible for overseeing this research project recommended the use of this format to integrate ROADZ with INROADS. The TOC also recommended the conversion of ROADZ from DOS to Windows operating environment. These recommendations will be implemented as part of a new research project in 1999-2000.

Chapter 1 Project Description and Objectives

Problem Statement

Optimizing earthwork is an important objective of a good road design. This is especially true while designing roads in mountainous terrain. Roadway designers use various computer programs to automate and simplify many routine tasks required in road design. This includes earthwork computations.

The optimization capabilities of different computer programs can differ substantially. But all commonly used road design software are similar in one aspect. They do not account for earthwork optimization explicitly. This is true of INROADS, the software used by the Idaho Transportation Department (ITD) for road design.

Project Description

Small changes in elevations of vertical points of intersections (VPI) can result in significant earthwork savings when designing roads. ROADZ is a road design software that can optimize earthwork, and it had the potential of fulfilling this need. This project resulted from ITD's desire to investigate potential earthwork savings from the use of ROADZ.

ROADZ Background

The origins of ROADZ goes back to the 60's when the computer program, Road Design System (RDS), was developed by the United States Forest Service (USFS). RDS was designed to adjust the profile grade VPI to balance the earthwork. It was later renamed to EASY (EArthwork SYstem). The current version of ROADZ was developed from EASY, and it runs under the DOS operating system.

Though it was developed originally for low-standard forest service roads, ROADZ had two features that indicated the suitability of this software to higher-standard roads. First, the method used by ROADZ to compare the profile grade with the mass diagram is the same for any design. In the final stages of most designs small changes in the elevations of the VPI's are effected to arrive at a more optimal earthwork. The mass diagram is often consulted as the basis of this change. ROADZ permits the better earthwork design to be arrived at sooner and more accurately.

Secondly, the higher the roadway design standard, the further apart the VPI's tend to be spaced. This minimizes the tendency toward excessive rolling grades. Thus, ROADZ solution appears to have the potential to be acceptable even for higher-standard roads. This research project was designed to test the suitability of ROADZ to optimize earthworks for higher-standard roads in Idaho.

OBJECTIVES

The first objective of the project was to select a sample of recently designed road segments and give them a "re-design" using the earthwork optimizing program, Optimized Earthwork (OPTEW), one of the modules of the ROADZ suite of programs. An additional objective was to investigate ways of incorporating OPTEW into ITD's road design procedures.

SCOPE

The above objectives were intended to be fulfilled in three steps outlined below:

1. Conduct a "re-design" of sections of representative highways

   1.1. In consultation with the Technical Oversight Committee (TOC) select sections of representative highways to include in the study.

   1.2. Obtain road design data for the selected sections. The data will include original ground surface, horizontal and vertical alignments, the final design surface, cross-sections, and template data.

   1.3. Redesign the selected sections using ROADZ.

2. Investigate how OPTEW can be incorporated into ITD's road design procedures.

   2.1. Compare the ROADZ results with existing design and determine whether earthwork savings including haul are significant.

   2.2. If the savings are found to be significant in Step 2.1, conduct a detailed investigation of how OPTEW can be incorporated into ITD's road design procedures.

3. Report the findings to ITD.

Report Structure

Following this introductory chapter, the road sections selected for analysis will be described in Chapter 2. The next three chapters will describe the analysis for the three segments that were analyzed. Chapter 6 will deal with the integration of the earthwork optimizing features of ROADZ with ITD's road design procedures. The report ends with conclusions and recommendations in Chapter 7.

Chapter 2 Selection of Road Segments

The criteria for selecting road segments for analysis were simple. The road segments would have to be at least 2 miles long, the design would have to be recently completed, the design data had to be readily accessible, and they would need to have a reasonable amount of earthwork in them. ITD was approached with these criteria and they were able to come up with the following candidate projects for evaluation.

Road Segment 1

US 95 Near Parma

This segment is part of the US 95 reconstruction near Parma and is slightly over 5 miles long. The vertical profile consists of vertical curves of length between 200 to 1400 ft. The steepest grade on this section is slightly over 3%, and it is a downward slope of length about 1000 ft. ITD computed cut and fill volumes for this section are about 440,000 and 384,000 cu yd. Figure 1 depicts a 1½ mile portion of the vertical profile of this road.

Road Segment 2

SH 3 Arrow to Turkey Farm

This is the first segment of a 7 km-long road improvement project on SH 3 in Nez Perce County between Arrow to Little Potlatch Creek by way of Turkey Farm. The segment selected for study is about 3½ km long and is from Arrow to Turkey Farm. The design vertical grade profile for this improvement project is shown in Figure 2.

As is evident from the profile plot there is a large hump on the ground profile along the alignment between Stations 1+250 and 1+500. This is reflected in the high earthwork volumes of about 474,000 cu yd of cut and 216,000 cu yd of fill required in the ITD design. The steepest grade on this segment is about 4.6% and it comes after a sustained up-grade of more than 2 km.

Road Segment 3

SH 3 Turkey Farm to Little Potlatch Creek

The last segment studied is the second part of the two-part road improvement project on SH 3 in Nez Perce County. The segment is about 3¼ km long. Figure 3 shows the ground profile along the alignment of this road; the designed grade profile based on BSU's design is also shown. The BSU longitudinal profile shown in the figure is based on ITD's design and is obtained by making minor adjustments to the VPI's to optimize earthwork. Such adjustments in the VPI's do not change the design profile appreciably, a fact that will be demonstrated later in this report. The grade profile shown in the figure closely resembles the profile designed by ITD.

There are 7 vertical curves on this section of SH 3. The steepest grade is about 4.8%, and the terrain is undulating. The elevation on the road varies between 281 and 295 m.

Chapter 3 Analysis of Road Segment 1

The OPTEW Earthwork Optimization Process

OPTEW stands for Optimized Earthwork, which is a program in the suite of road design programs collectively known as ROADZ. All earthwork optimization in this project was done using OPTEW. The optimization process used by this program is described first before the analysis results are presented.

The goal of OPTEW is to achieve a mass diagram with minimum haul. How OPTEW accomplishes this task is explained below.

OPTEW relates the existing mass diagram to the profile grade. Essentially, OPTEW estimates the mass change needed in the vicinity of each VPI. At the same time OPTEW determines to what extent the mass will change if the corresponding VPI is raised or lowered one unit (foot or meter) of elevation. This latter value is called the UNIT MASS. The desired mass change is then divided by the unit mass to compute the elevation change needed at that VPI.

The desired mass change for a given VPI elevation change is determined by using least-squares/best-line fitting mathematics. In manual methods this same consideration was done graphically with a straight edge and a mass diagram plot. The intersections of the adjacent best lines set the expected starting and ending mass values. The difference between these values is the desired mass change required for that particular VPI.

All of the unit mass values and the corresponding VPI elevation changes are then applied to the profile grade to determine the resulting grades. Examples of this procedure will be provided later.

Optimization for Segment 1

Procedure for Analysis

Provided below is a listing of steps that were followed in the analysis for this research project. This procedure was used for all three segments.

1. Acquire ITD design, original terrain files, and plan/profile sheets.
2. Convert the cross sections into ROADZ input format.
3. Key in the design specifications including templates, slope specifications, and compaction factors.
4. Key in the vertical and horizontal alignments.
5. Create a design file by inputting the data created in Steps 2, 3, and 4.
6. Run ROADZ's superelevation program.
7. Make several SPEC and QUAN runs until the quantities closely matched the ITD design. Several runs were required due to the numerous sections where there were non-standard widening due to waste. (SPEC and QUAN are ROADZ programs.)

8. Compute and enter into the design file a compaction factor that gave ITD's design a balanced look. (This step was not required for the Segment 1; it was required for Segment 3.)
9. Execute the ROADZ optimization program, OPTEW. Adjust the related VPI's and run the earthwork program, QUAN, again.
10. Make the required number of minor VPI changes to effect a balance comparable to the ITD balanced design.

Optimization Results

The lower part of Figure 1 depicts the mass diagrams based on ITD'S and BSU's designs. Since ITD's mass diagram is balanced (starts and ends at zero cumulative volume) Step 8 in the procedure outlined above was not required for this segment. The mass diagram labeled "ITD Mass Curve" in the figure is based on earthwork quantities obtained from ROADZ using data provided by ITD. In other words, the mass diagram is based on the output from ROADZ obtained after Step 7 in the above procedure. The mass curve labeled "ROADZ Mass Curve" is the mass curve based on the optimized design obtained after Step 10.

The results obtained from this procedure are listed below in Table 1.

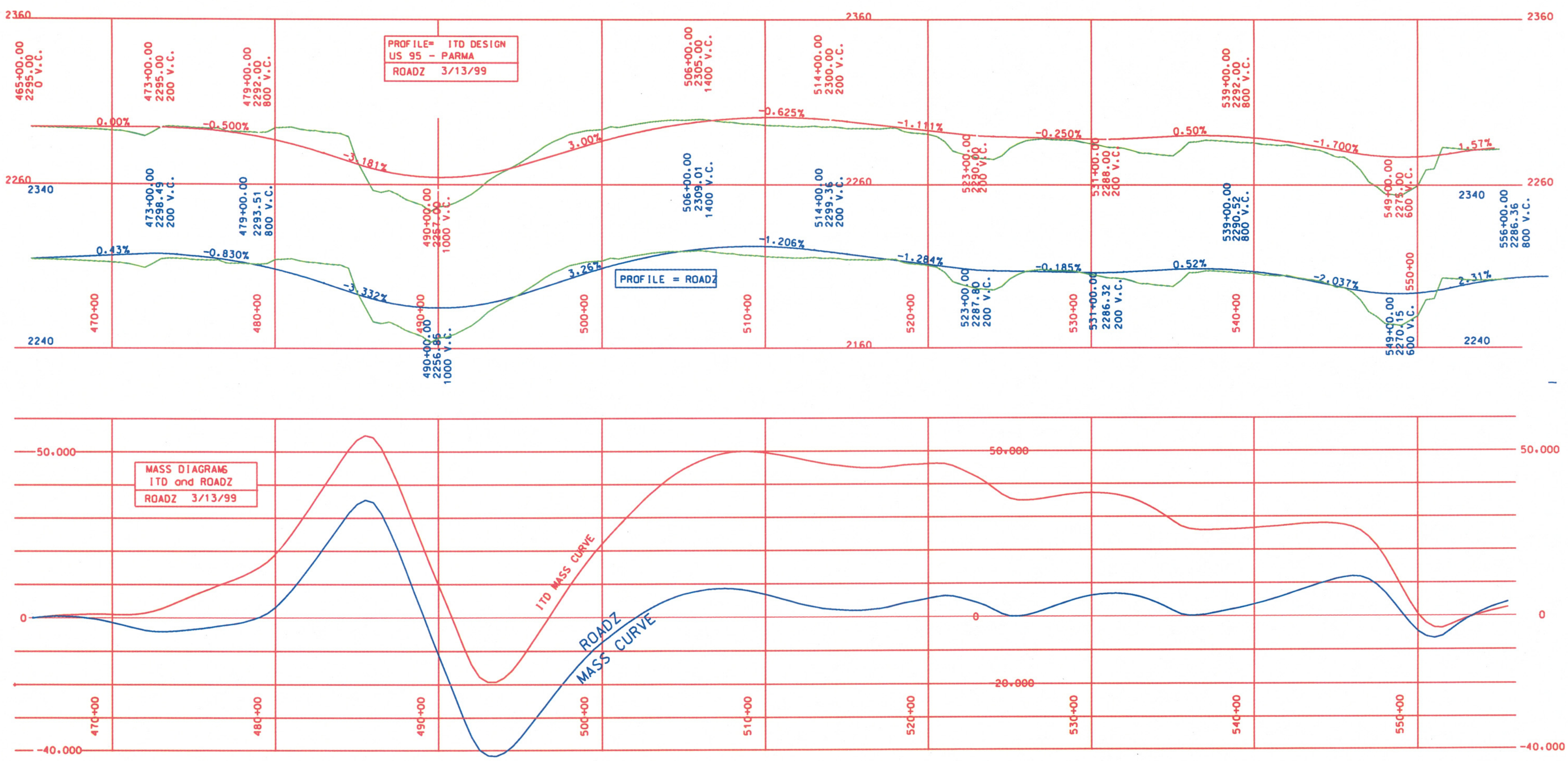
	Cut (cu-yd)	Fill (cu-yd)	Haul (mi-yd)
ITD Design	439,574	383,871	----------
ROADZ Output using ITD data	439,926	384,198	105,440
ROADZ Output after 1 optimizing run	415,902	361,540	45,617
ROADZ Output after 2 optimizing runs	401,857	352,104	36,078
Quantity reduction due to optimizing	38,069	32,094	69,362
Percentage reduction due to optimizing	8.7%	8.4%	65.8%

Table 1: Earthwork Summary for Segment 1

Figure 1 shows that the difference in profile grade between ITD and ROADZ designs is minimal. The principal difference between the two designs is seen in the mass diagrams in the figure. The ROADZ mass diagram stays close to the zero cumulative volume line. As a result the reduction achieved in the haul quantity is huge; almost 66% in this case.

It should be kept in mind, however, that the reduction in quantities shown in the table above can not be realized, if the VPI changes suggested by OPTEW are not acceptable to the designer. It is possible for some of the proposed changes to violate design constraints. It is because of this that ROADZ does not automatically apply the proposed changes to effect the next earthwork run. Rather, ROADZ leaves it up to the designer to review proposed changes and thus accept, modify, or reject them one by one. All in all, however, the subsequent earthwork runs will likely show improvement over the non-ROADZ analyzed runs.

Figure 1: US 95 - Parma



Chapter 4 Analysis of Road Segment 2

Optimization Results

Figure 2 depicts the vertical profile for this segment. Because of the hump in the original ground profile earthwork quantities are relatively higher for this segment as shown in Table 2 below.

	Cut (cu-m)	Fill (cu-m)	Haul (km-cu-m)
ITD Design	474,161	216,386	----------
ROADZ Output using ITD data	471,404	218,059	1,511,534
ROADZ Output after 1 optimizing run	305,785	273,376	231,340
ROADZ Output after 2 optimizing runs	305,495	302,865	66,021
Quantity reduction due to optimizing	165,909	(84,806)	1,445,513
Percentage reduction due to optimizing	35.2%	(38.9)%	95.6%

Table 2: Earthwork Summary for Segment 2

The table depicts some peculiar results that need highlighting. First, there is an increase in fill quantity. There is a relatively huge reduction in cut volume; consequently, there is a dramatic reduction in haul quantity.

What is not shown in the above table is the increase in retaining wall area under ROADZ design. For the ITD design, the area of retaining wall needed was 2,100 sq m. For ROADZ design with 2 optimization runs the area of retaining wall needed is 5,100 sq m. Thus in this project the designer needs to decide between decreasing earthwork and increasing retaining wall. It is entirely possible that the optimization recommended by OPTEW may not be realized for this case.

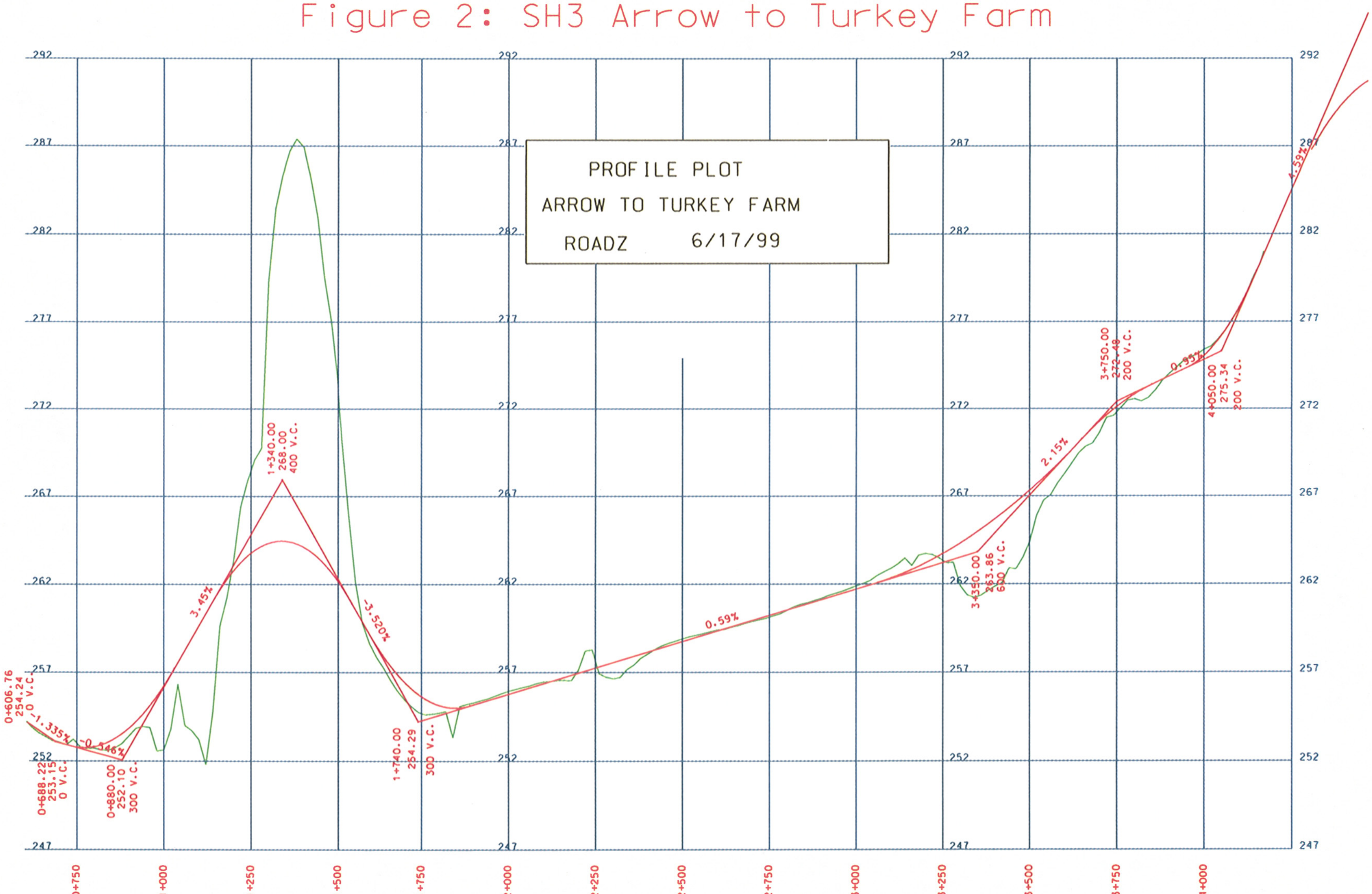
Presented below in Table 3 is a listing of the optimized elevations and unit mass obtained from OPTEW.

Station	VPI Elevation	Grade	VPI Elevation Change	Unit Mass
0+606.7	254.24		0.00	717
0+688.2	252.96	-1.5689	-0.19	2876
0+880.0	252.38	-0.3014	0.28	7743
1+340.0	278.71	5.7239	10.71	20508
1+740.0	255.55	-5.9469	1.26	28232
3+350.0	264.13	0.5330	0.27	27455
3+750.0	271.80	1.9185	-0.68	8802
4+050.0	275.89	1.3637	0.55	13686
4+484.0	295.55	4.3919	-0.36	21573

Table 3: Optimized Elevations and Unit Mass for Segment 2

The VPI elevations and profile grades shown in Table 3 are not depicted in Figure 2. Figure 2 is a plot of the original ITD data. The VPI elevation change values in the table show the extent of VPI adjustment required by OPTEW to realize the earthwork savings shown in Table 2. For example, the VPI at station 1+340.0 required an elevation adjustment of 10.71 m to achieve full optimization.

Figure 2: SH3 Arrow to Turkey Farm



Chapter 5 Analysis of Road Segment 3

Optimization Results

Figure 3 depicts the profile grade for the road segment on SH 3 between Turkey Farm and Little Potlatch Creek. The grade shown is the BSU design from ROADZ. As mentioned before, for most projects the change in the profile grade is minimal. An evidence of that was seen in Figure 1 where both profiles were plotted and the difference in the two appeared to be negligible.

Figure 4 shows the mass diagram plots for three cases: ITD original design, ITD modified for balanced design, and the optimized design. Figure 5 is a blowup of the road profile in the vicinity of Stations 4+484.00 and 4+964.00, and it illustrates how OPTEW achieves its optimization by making adjustments in the VPI's. Table 4 below is a listing of the optimized elevations and unit mass for this segment.

Station	VPI Elevation	Grade	VPI Elevation Change	Unit Mass
4+170.0	281.43		0.00	7293
4+484.0	297.14	5.0032	0.69	18346
4+964.0	279.95	-3.5813	-0.95	20163
5+394.0	298.22	4.2488	0.87	20921
5+854.0	289.56	-1.8826	-0.69	23471
6+294.0	293.03	0.7886	0.03	18464
6+744.0	280.12	-2.8389	0.12	12900
7+384.0	286.57	1.0078	0.37	8015
7+465.4	286.66	0.1154	0.00	892

Table 4: Optimized Elevations and Unit Mass for Segment 3

In comparing Tables 3 and 4 it is noteworthy that the changes in the latter table are much smaller than in the former. The unit mass values, however, are generally higher for Segment 3 compared with those for Segment 2.

Earthwork Summary

The summary of earthwork quantities obtained for Segment 3 is shown in Table 5 below.

	Cut (cu-m)	Fill (cu-m)	Haul (km-cu-m)	End Mass (cu-m)
ITD Design	151,270	166,995	84,533	15,726
ITD Balanced Design	151,270	166,995	55,045	6
ROADZ Optimized Design	138,352	152,731	27,362	10
Quantity reduction due to optimizing	12,918	14,264	27,683	----------
Percentage reduction due to optimizing	8.5%	8.5%	50.3%	----------

Table 5: Earthwork Summary for Segment 3

Figure 3: SH3 Turkey Farm to Little Potlatch Creek
Profile Plots – BSU Design

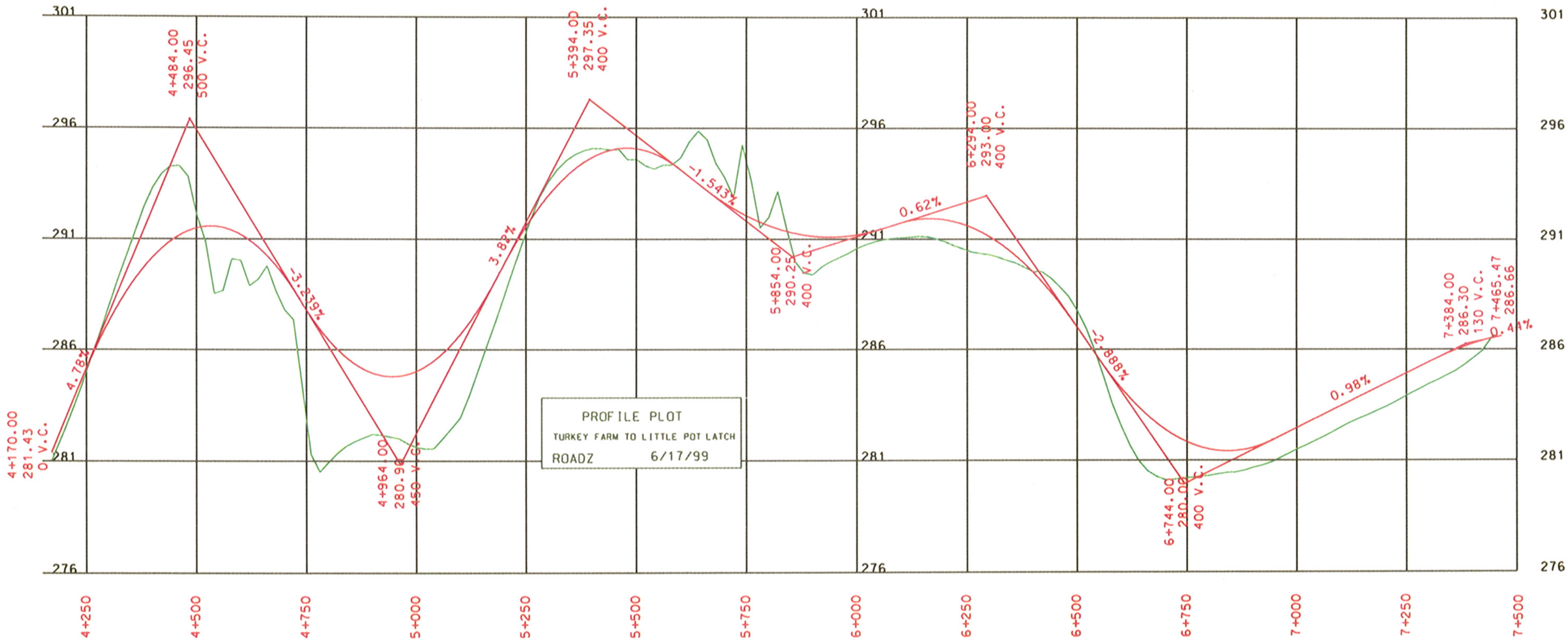
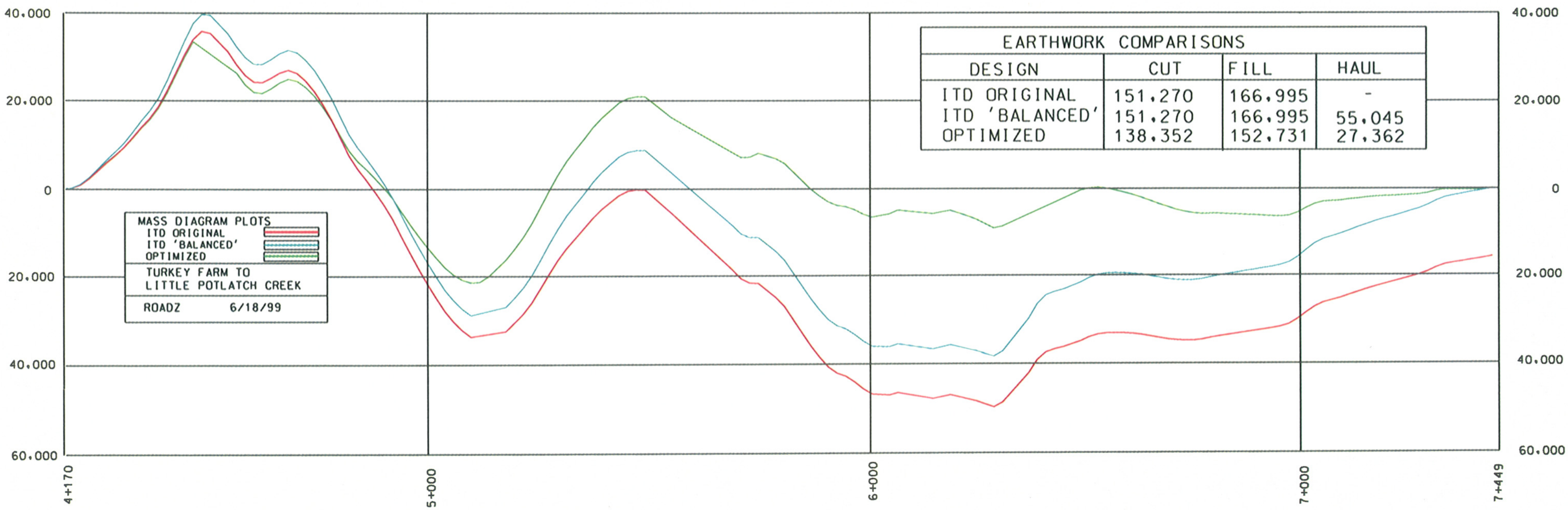


Figure 4: SH 3 Turkey Farm to Little Potlatch Creek
Mass Diagram Plots

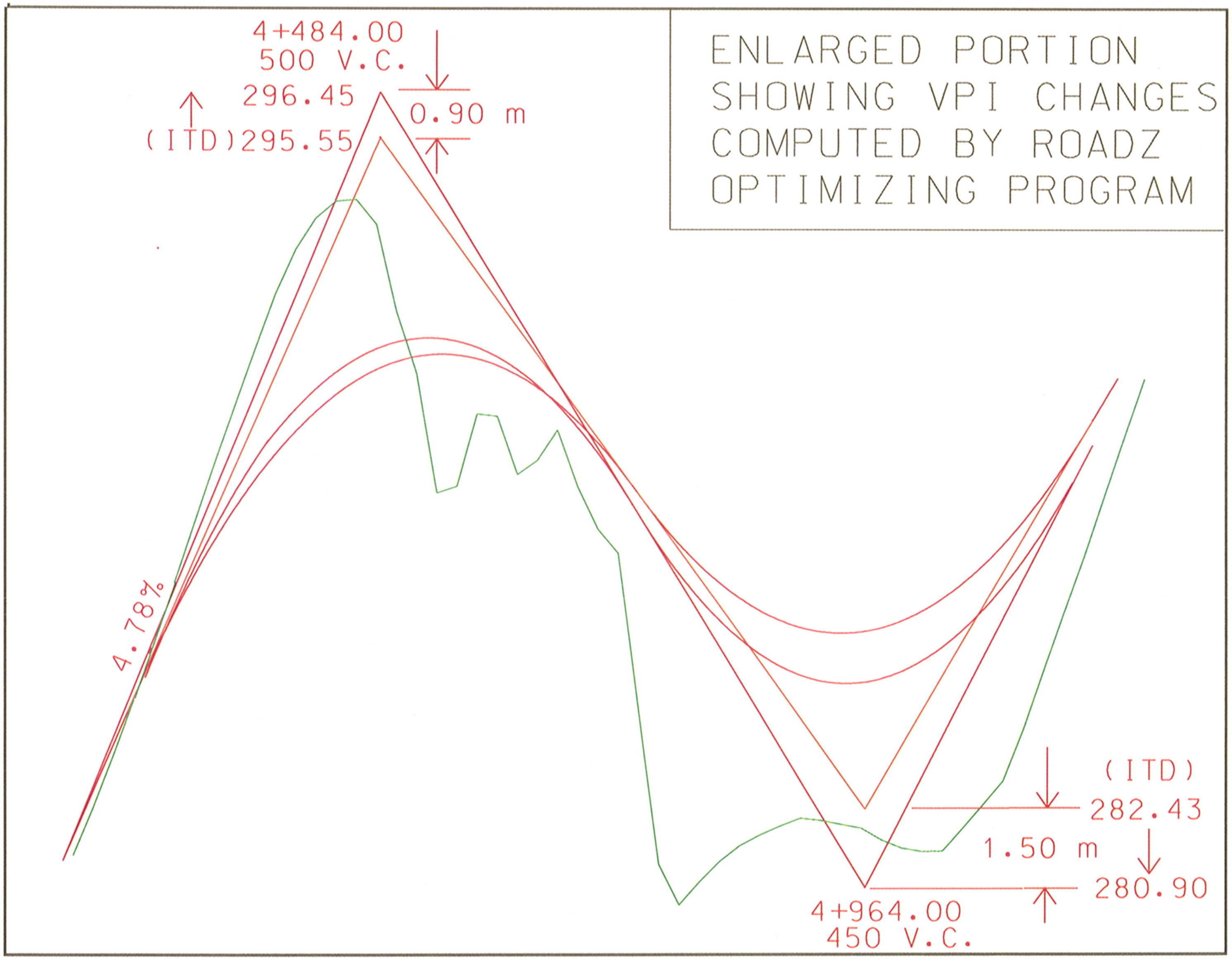


EARTHWORK COMPARISONS

DESIGN	CUT	FILL	HAUL
ITD ORIGINAL	151.270	166.995	-
ITD 'BALANCED'	151.270	166.995	55.045
OPTIMIZED	138.352	152.731	27.362

Figure 5: SH 3 Turkey Farm to Little Potlatch Creek

VPI Changes Blowup



Notice that there is an additional column in this table that shows the end mass volume because the original ITD design had an unbalanced mass diagram. In this particular case, the ending mass was about 16,000 cubic meters short.

In the absence of a computerized earthwork optimizing program such as OPTEW one would have to do two or three more earthwork runs using a modified profile grade to achieve a nearly-balanced mass diagram. (A balanced mass diagram is one that ends with zero mass.) In this particular drawing, a uniform change in all the VPI elevations of -0.12 meters would have produced a nearly-balanced mass curve. This mass diagram is represented by the blue mass line in Figure 4.

When an optimizing program such as OPTEW is available the analysis starts with the initial mass curve, shown in red in Figure 4. After one analysis, assuming all the VPI elevation changes are acceptable, the resulting mass curve would resemble the green mass curve line. As we can be readily seen, there is a noticeable reduction in the haul between the green and blue mass curves. The reduction in this case is just over 50%. There was also over 8% reduction in excavation quantities as shown in Table 5.

OPTEW strives to achieve a mass diagram with minimum haul by relating the existing mass diagram to the profile grade. Essentially, OPTEW estimates the mass change needed in the vicinity of each VPI. Then the desired mass change is divided by the unit mass to compute the elevation change needed at that VPI. For instance, the desired mass change at VPI 5+394 was about 18,200 cu m. By dividing 18,200 by 20,163 an elevation change of +0.87 m is calculated.

As mentioned before this information is provided to the designer who has to decide whether or not such changes can be made without endangering the quality of the design. Not only do the changes reduce the haul, but reduction of excavation also usually accompanies this technique.

Again as mentioned before not all VPI changes recommended by OPTEW can be implemented. When such is the case, the unchanged mass is compensated by over-compensating at the nearby VPI's.

Chapter 6 Integrating ROADZ with ITD Road Design

One of the objectives of this research project was to investigate ways of integrating OPTEW with ITD's road design process, if the earthwork savings in the test segments were found to be significant. The TOC believed that the savings demonstrated in the test segments warranted this investigation, and accordingly various alternatives were examined.

One of the alternatives examined was to combine the optimization procedure with the road design procedure to create a seamless integrated process. ITD uses INROADS for road design, and for this approach to be successful, ROADZ has to be able to access the intermediate binary files generated by ROADZ to modify the VPI elevations for earthwork optimization. This approach would necessitate negotiation with the Integraph Corporation to gain access to the binary files.

Yet another alternative considered was to treat ROADZ and INROADS as stand-alone programs with the designer acting as the interface between the two programs. This alternative would require the intervention of the designer at each successive iteration between earthwork computation and optimization.

As was described in previous chapters, the role of the designer in accepting the recommendations generated by OPTEW is important. Viewed in this context, the second alternative appears to be meritorious.

Yet another alternative was to wait for the adoption of the Engineering and Survey Exchange (EAS-E) data format by AASHTO before deciding on the proper course of action towards integration of ROADZ with InRoads. The EAS-E format, apparently, allows easy exchange of data between vendor software and user programs. A member of the TOC indicated that the adoption of this format by AASHTO was imminent.

The TOC also recommended that ROADZ be converted from DOS to Windows operating environment. As this task was not part of the original scope of work, it was set aside for possible future projects. As there were many unresolved issues regarding integration it was also set aside for future projects.

Chapter 7 Conclusions & Recommendations

The project provided mixed results. In two of the three segments savings between 50 to 60% in mass haul and 8 to 9% in cut and fill were realized. The changes in VPI elevations suggested by the optimizing program for these test segments appear to be reasonable. The two segments are US 95 near Parma and SH 3 between Turkey Farm to Little Potlatch Creek.

In the third segment, SH 3 between Arrow and Turkey Farm, significant savings in cut and haul were achieved. The fill, however, increased. Furthermore, there was an increase in retaining wall requirements. There was a peculiarity in this third segment that may have contributed to this problem. This peculiarity was in the form of a large hump in the original ground profile along the alignment of this road segment.

It also became apparent from this study that changes recommended by earthwork optimization programs need to be evaluated carefully by the road designer before acceptance. It became clear that the skill and experience of the designer will play a crucial role in arriving at efficient road designs no matter what software is used in the design process.

Even though there was a segment, among three, that did not benefit from earthwork optimization, it is recommended that further investigation into making the optimization feature available to ITD designers be pursued. It is also recommended that the earthwork optimization feature of ROADZ be converted from a DOS environment to a Windows based environment. Finally, it is strongly recommended that ITD provide adequate training to its road designers.